PRAMANA
— journal of
physics

pp. 1–15

Working Group Report: Neutrino and Astroparticle Physics

Coordinators: Srubabati Goswami and Raghavan Rangarajan
Working Group Members: K. Agashe, A. Bandyopadhyay, K. Bhattacharya, B. Brahmachari, C. Burgess, E.J. Chun, D. Choudhury, P.K.Das, A. Dighe, R. Godbole, S.Goswami, N. Gupta, M. Kaplinghat, D. Indumathi, J. Forshaw, Y.Y. Keum, B. Layek, D. Majumdar, N. Mahajan, P. Mehta, R.N. Mohapatra, N. Mondal, S. More, Y. Nir, S. Pakvasa, M.K. Parida, M. Ravikumar, G. Rajasekaran, P. Ramadevi, R. Rangarajan, S.D. Rindani, D.P. Roy, P. Roy , N. Sahu, A. Samanta, Y. Shadmi, A.M. Srivastava, S. Uma Sankar, R. Vaidya, U. Yajnik

Abstract. This is the report of neutrino and astroparticle physics working group at WHEPP-8. We present the discussions carried out during the workshop on selected topics in the above fields and also indicate progress made subsequently. The neutrino physics subgroup studied the possibilites of constraining neutrino masses, mixing and CPT violation in lepton sector from future experiments. Neutrino mass models in the context of abelian horizontal symmetries, warped extra dimensions and in presence of triplet Higgs were studied. Effect of threshold corrections on radiative magnification of mixing angles was investigated. The astroparticle physics subgroup focused on how various particle physics inputs affect the CMBR fluctuation spectrum, and on brane cosmology. This report also contains an introduction on how to use the publicly available code CMBFAST to calculate the CMBR fluctuations.

Keywords. neutrino oscillation, neutrino mass models, CMBR, dark energy, branes

PACS Nos 14.6q, 98.80.Cq, 11.25.-w

1. Introduction

The working group on Neutrino and Astroparticle Physics had two main themes. Neutrinos and Cosmology.

The Neutrino Physics subgroup studied the possibilites of determination of the neutrino oscillation parameters using almost pure ν_μ beams in future superbeam experiments as well as using pure ν_e beams in future β-beam experiments. CPT violation in neutrinos and possible outcomes of this in long baseline experiments and neutrino factories was posed as a possible area of further study. Scenarios where each of the three neutrino flavours is contemplated to be a pseudo-Dirac state consisting of one active and one sterile partner and the possible effects of this on Supernova neutrino detection emerged as an intersting problem to be investigated further. Neutrino masses in the context of Abelian horizontal symmetries in the framework of Froggat-Nielsen mechanism were explored. Neutrino masses and mixings in warped extra dimensions were also looked into. The effect of threshold corrections on radiative magnifications and mixing for quasidegenarate neutrinos were studied.

Triplet Higgs models for neutrino masses and possible tests of these in upcoming collider experiments were discussed. Finally there were disucssions on the possible areas that can be further explored in leptogenesis.

The efforts of the Astroparticle Physics subgroup were focused on understanding how fluctuations in the cosmic microwave background radiation are affected by various particle physics inputs and on brane cosmology. Calculating the effects of particle physics inputs, such as neutrino properties, on the CMBR requires one to numerically solve the evolution of photons from decoupling to the presentera. Therefore, this report contains a brief introduction on how to use CMBFAST, the publicly available code that allows one to calculate CMBR fluctuations as a function of various input parameters. We then include a list of some particle physics related issues that can have an effect on the CMBR fluctuations and discuss how CMBFAST should be amended to study these effects. We further present the results of some prelimnary efforts to modify the code. In brane cosmology, discussions focused on understanding inflation and reheating in the context of brane universes, and on explaining the origin of dark energy in the context of supersymmetric ADD models.

Below we disuss the work done in these two subgroups in two different sections.

2. Neutrinos

In the neutrino sector the two focal themes were *Precision Determination of Neutrino Oscillation Parameters* and *Neutrino mass models*. The three plenary talks in these topics were *Long baseline neutrino experiments by S. Uma Sankar, Neutrino mass models and proton decay by R. N. Mohapatra, and India Based Neutrino Observatory by D. Indumathi* In addition the following seminars were arranged:

• High Energy Astrophysical Neutrinos —S. Pakvasa
• A to Z symmetries of the Neutrino Mass Matrix —G. Rajasekaran
• CPT violation with Atmospheric Neutrinos —Poonam Mehta
• Radiative magnification of mixing for quasi degenerate neutrinos : Effect of threshold corrections —M.K.Parida

Apart from this there were short presentations by the members of the Indian Neutrino Observatory (INO) collaboration in a session devoted to discussion on various issues related to the INO experiment. The working group formation and discussions of topics were held on 8th January, 2004. Probir Roy led the disucussions on Neutrinos Mass models. The following topics were discussed and possibilites of further investigations explored:

•PseudoDirac Neutrinos and their effect on supernova neutrino signal
•Probing θ_{13} and sign of Δ_{31} with almost pure ν_μ beams
• Studying Neutrino Oscillation parameters with pure ν_e beams
• Discussion on INO
• CPT violation and possible effects in LBL experiments
• Neutrino Masses in warped extra dimension
• Supersymmetric Triplet Higgs Model for M_ν: LE flavour violation and HE collider test
• Leptogenesis
• Neutrino masses with Abelian Horizontal Symmetries

• Radiative Magnification of mixing for quasi degenerate neutrinos : Effect of threshold corrections

2.1 PseudoDirac Neutrinos and their effect on supernova neutrino signal
A. Bandyopadhyay, D. Choudhury, A. Dighe, S. Goswami, D. Majumdar, P. Mehta, S. Pakvasa

We considered the scenario where each of the three active neutrinos may be considered to be a Pseudo-Dirac Neuttrino, composed of one active and one sterile state. Recently such a scenario has been considered in [1]. The mass difference between each paired state is very small i.e they are almost degenerate and maximally mixed with $\Delta m^2 \sim 10^{-19}$ eV^2. In such a picture one will have additional MSW resonances inside the supernova core. The mass difference of $\Delta m^2 \sim 10^{-19}$ eV^2 will also give rise to oscillation effects on the way from supernova to earth. The survival and conversion probabilities for this scenario will therefore be different from the standard three generation picture and the effect on the supernova neutrino signal may therefore be different. The propgation of the neutrinos inside the supernova for a such a scenario was studied during the workshop. While this study was going on during the workshop a similar paper came out in the spires [2]. Efforts are on to do a more detailed study.

2.2 Probing θ_{13} and sign of Δ_{31} with almost pure ν_μ beams
A. Bandyopadhyay, A. Dighe, P.K. Das, S. Goswami, P. Mehta, S. Uma Sankar

We propose to combine two ν superbeams at different baselines :
• ν superbeam from JHF with L = 295 km and E = .75 GeV
• NuMI-Off Axis ν superbeam with L = 732 km and E = 1.5 GeV
The aim is to look for matter effects using two different baselines So one should first look at the appearance mode $\nu_\mu \to \nu_e$ and vary $\sin^2 2\theta_{13}$ between 0.1 to 0.25 for which terms $\sim \Delta_{21}/\Delta_{31}$ can be neglected Then one can determine the signal at J2K experiment for the above values of θ_{13} and check if the sign of Δ_{31} can be probed from NuMI Off-Axis experiment for θ_{13} in the above range. The next step will be to include the terms $\sim \Delta_{21}/\Delta_{31}$. The numerical work is in progress.

2.3 Studying Neutrino Oscillation parameters with pure ν_e beams
A. Bandyopadhyay, S. Goswami, P. Mehta, S. Uma Sankar

Radioactive ions accelerated to high energy decay through beta process and give pure $\bar{\nu_e}/\nu_e$ beams which are called beta-beams in the literature [3]. The advantages in these are
• single neutrino flavour
• well known energy spectrum and intensity
• strong collimation
We studied the possibility of using low energy beta beams to probe solar neutrino oscillation parameters. For $\Delta m^2 = 7.2 \times 10^{-5}$ eV^2 maximum oscillation for 50 MeV ν_e at

732 km (CERN to Gran Sasso) However event rates for such low energy beta beams are very low at such distances and therefore the conclusion is low energy beta beams are not suitable for probing oscillation parameters relevant for the solar neutrino problem.

2.4 Discussion on INO
S. Chattopadhyaya, A. Dighe, D. Indumathi, S. Goswami, D. Majumdar, P. Mehta, N. Mondal, G. Rajasekaran, A. Raychaudhury, D.P. Roy, P. Roy, A. Samanta, S. Uma Sankar

Following short presentations were given

1) ICAL and some present/near future experiments – S. Goswami
2) RPC studies for ICAL@INO – N. K. Mondal
3) Can we study matter effects with ICAL ? – D. Indumathi
4) Physics reach of NuMI off-axis experiment – S. Uma Sankar
5) β beams, superbeams and neutrino factory beams – P. Mehta
6) Relationship between neutrino and muon energies in QE and Single pion processes – D. P. Roy

2.5 CPT violation in neutrinos at Longbaseline Experiments
Amol Dighe and Poonam Mehta

The interactions of neutrinos may involve a CPT-odd term of the form $\bar{\nu}_L^\alpha b^\mu_{\alpha\beta} \gamma_\mu \nu_L^\beta$, where α and β are flavour indices, and the elements $b^\mu_{\alpha\beta}$ are in general complex [4]. This term modifies the neurino effective Hamiltonian, which becomes (in the ultra-relativistic limit)

$$H_{\alpha\beta} = \frac{(mm^\dagger)_{\alpha\beta}}{2E} + b^0_{\alpha\beta} \quad . \tag{1}$$

Here m is the neutrino mass matrix in the flavour basis. CPT violation arises from the fact that $b^0_{\alpha\beta}$ changes sign when going from neutrinos to antineutrinos.

The special case of two neutrino mixing, where in addition $mm^\dagger$ and b^0 are both diagonalized by the same unitary matrices, has already been studied. It has been shown that at future neutrino factories or at detectors with muon charge identification capabilities, one can constrain the difference in b^0 eigenvalues to $\delta b \lesssim 10^{-23}$ GeV [4,5]. The constraints from reactor and solar neutrino experiments have also been estimated [6].

The general case, where the structure of b^0 is indepenent of the structure of $mm^\dagger$, needs to be studied. This involves taking into account the extra mixing angle as well as an additional complex phase between the diagonalizing unitary matrices. In that general framework, one should first calculate the current limits on the elements of $b^0_{\alpha\beta}$, if any, from the solar, atmospheric and reactor data available. Then one can proceed to compare the extent of these effects at long baseline experiments and neurino factories, and devise strategies for disentangling these from matter effects and CP violating effects at these detectors.

2.6 Neutrino masses with Abelian Horizontal Symmetries
S. Goswami, D. Indumathi, Y. Shadmi, Y. Nir

The mass hierarchy in the charged lepton and quark sectors and the small quark mixings call for an explanation. One of the most attractive frameworks that provide a natural explanation is that of the Froggatt-Nielsen (FN) mechanism. One assumes an Abelian horizontal symmetry that is spontaneously broken at a scale somewhat lower than some high flavour scale M_F. We studied the application of such models to the neutrino sector, with the hope of explaining the observed neutrino mass and mixing parameters. If the neutrinos are Majorana particles then there is an additional scale, M_L, which is the scale of lepton number violation. The existence of this high scale explains the smallness of neutrino masses through the see-saw mechanism. We aim to explore if the existence of this additional scale, on top of the Froggatt-Nielsen scale, can explain the special flavor features that are observed in the neutrino sector. We studied some specific examples in a simplified two neutrino framework during WHEPP. This work was further continued in [7]. It was found that the presence of this scale in the framework of the FN mechanism can give rise to flavour parameters that have a different hierarchy than the charged fermions. Moreover, unique features, such as inverted hierarchy or pseudo-Dirac state, can appear in the neutrino sector. We continue to correspond and exchange ideas related to this topic.

2.7 Neutrino masses and mixings in warped extra dimensions
K. Agashe, P. Das, A. Dighe, P. Mehta and P. Roy

Consider the Randall-Sundrum (RS1) model [8] which is a compact slice of AdS$_5$,

$$ds^2 = e^{-2k|\theta|r_c}\eta^{\mu\nu}dx_\mu dx_\nu + r_c^2 d\theta^2,\ -\pi \leq \theta \leq \pi, \tag{2}$$

where the extra-dimensional interval is realized as an orbifolded circle of radius r_c. The two orbifold fixed points, $\theta = 0, \pi$, correspond to the “Planck” and “TeV” branes respectively. In warped spacetimes the relationship between 5D mass scales and the mass scales in the effective 4D description depends on the location in the extra dimension through the warp factor, $e^{-k|\theta|r_c}$. This allows large 4D mass hierarchies to naturally arise without large hierarchies in the defining 5D theory, whose mass parameters are taken to be of the order of the observed Planck scale, $M_{Pl} \sim 10^{18}$ GeV. For example, the 4D massless graviton mode is localized near the Planck brane while Higgs physics is taken to be localized on the TeV brane. In the 4D effective theory one then has $M_{\rm weak} \sim M_{Pl}e^{-k\pi r_c}$, and a modestly large radius, $k\pi r_c \sim \log{(M_{Pl}/\mathrm{TeV})} \sim 30$, can then accommodate a TeV-size weak scale. We consider a scenario where the SM gauge and fermion fields are allowed to be in the bulk, and show that this can natutrally give the observed pattern of neutrino masses and mixings.

The profile in the fifth dimension of the wavefunction of the massless chiral mode of a $5D$ fermion (identified with the SM fermion) is controlled by the c-parameter [9,10]. For $c > 1/2$ ($c < 1/2$) the zero mode is localized near the Planck (TeV) brane, whereas for $c = 1/2$, the wave function is flat. We choose $c > 1/2$ for light fermions so that the effective ultraviolet cutoff is much greater than TeV and the FCNC's are suppressed [10,11]. Also this naturally results in small $4D$ Yukawa couplings to the Higgs on the TeV brane without any hierarchies in the fundamental $5D$ Yukawa coupling [10,11].

We introduce 3 right-handed neutrinos (ν_R's) in the bulk, which have identical c values. The lepton number is taken to be broken only on the Planck brane, such that these ν_R's have Majorana mass terms localized on the Planck brane [12], and hence of the same order as the Planck scale. We choose the ν_R basis that diagonalizes the Majorana mass matrix, so that

$$M_R \propto \begin{pmatrix} \mathcal{O}(1) & 0 & 0 \\ 0 & \mathcal{O}(1) & 0 \\ 0 & 0 & \mathcal{O}(1) \end{pmatrix} \quad . \tag{3}$$

The ν_Ls and ν_R's give rise to a Dirac mass term

$$(m_D)_{ij} \sim (\lambda_{5D})_{ij}\, v \left(\frac{\text{TeV}}{M_{Pl}} \right)^{c_{iL}+c_{jR}-1} \tag{4}$$

where λ_{5D} is the $5D$ Yukawa coupling to Higgs (localized on the TeV brane) and the last factor comes from the profiles of the ν_L and ν_R zero-modes. We assume that the matrix λ_{5D} is anarchic (i.e., all its entries are of the same order) and $c_{\nu_{\mu L}} = c_{\nu_{\tau L}} < c_{\nu_{eL}}$. This gives

$$m_D \propto \begin{pmatrix} \mathcal{O}(\epsilon) & \mathcal{O}(\epsilon) & \mathcal{O}(\epsilon) \\ \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \\ \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \end{pmatrix} \quad , \tag{5}$$

where $\epsilon \sim (\text{TeV}/M_{Pl})^{c_{\nu_{eL}}-c_{\nu_{\mu L}}} \ll 1$.

Using Eqs. (3) and (5), we obtain the following see-saw formula for Majorana mass for light (mostly left-handed) neutrinos:

$$m_\nu = m_D M_R^{-1} m_D^T \propto \begin{pmatrix} \mathcal{O}(\epsilon^2) & \mathcal{O}(\epsilon) & \mathcal{O}(\epsilon) \\ \mathcal{O}(\epsilon) & \mathcal{O}(1) & \mathcal{O}(1) \\ \mathcal{O}(\epsilon) & \mathcal{O}(1) & \mathcal{O}(1) \end{pmatrix} \quad . \tag{6}$$

The larger of the two eigenvalues of the (2–3) submatrix of m_ν will naturally be $\mathcal{O}(1)$. If the smaller eigenvalues is $\mathcal{O}(\epsilon)$, then m_ν can be diagonalized by $U \equiv R(\theta_{12})R(\theta_{13})R(\theta_{23})$ where

$$\theta_{23} \sim \mathcal{O}(1) \quad , \theta_{13} \sim \mathcal{O}(\epsilon) \quad , \theta_{12} \sim \mathcal{O}(1) \quad , \tag{7}$$

so that we obtain two large mixing angles and one small mixing angle. Hence, we get a good fit to data for part of the parameter space (as shown in [13] for a different neutrino set-up in RS1). The requirement of $\mathcal{O}(\epsilon)$ eigenvalue of the (2–3) submatrix of m_ν may be viewed as a mild fine tuning. Ways of getting around this would be looked for in the continuation of this project.

2.8 Radiative Magnification of mixing for quasi degenerate neutrinos: Effects of threshold corrections

R.N. Mohapatra, M.K. Parida, G. Rajasekaran

In [14] it was demonstrated that unification of neutrino mixings with quark mixings takes place at high scales, but experimental data at low energies are explained due to radiative

magnification in the neutrino sector provided allthree neutrinos are quasidegenerate and possess the same CP. They obtianed $\Delta m^2_{21} \simeq (1.2-6.0)\times 10^{-4}$ eV^2 which is on the higher side of the solar neutrino data. In this work , completed during the WHEPP8 workshop they have estimated the threshold corrections.

Threshold effects on the mass basis is defined as

$$m_{ij} = m_i \delta_{ij} + m_i I_{ij} + m_j I_{ji} \tag{8}$$

A real transformation matrix U is used to express loop factors in the mass basis in terms of those in the flavour basis

$$I_{ij} = \sum_{\alpha,\beta} U_{\alpha i} U_{\beta j} I_{\alpha\beta} \tag{9}$$

The following model independent relations are derived using $\theta_{atm} = \pi/4$, $\theta_{CHOOZ} = 0$ under the assumption of minimal flavour violation with $I_{\alpha\beta} = diag I_e, I_\mu, I_\tau$

$$(\Delta m^2_{\odot})_{\rm th} \simeq 4m^2 \cos 2\theta_{\odot}[-I_e + \frac{1}{2}(I_\mu + I_\tau)]$$

$$(\Delta m^2_{atm})_{\rm th} \simeq 4m^2 \sin^2\theta_{\odot}[-I_e + \frac{1}{2}(I_\mu + I_\tau)]$$

$$(\Delta m^2_{\odot})_{\rm th} \simeq (\cot^2\theta_{\odot} - 1)(\Delta m^2_{atm})_{\rm th}$$

With allowed values of $\theta_{\odot}$ = 18 -40 $^{\rm deg}$, one gets $(\Delta m^2_{\odot})_{th} = (8.4 - 0.4)(\Delta m^2_{atm})_{th}$ demonstrating that both solar and atmospheric data cannot be explained purely by threshold effects. The RG effects and threshold effects both play important role in explaining the data.

Using sneutrino/chargino loops they evaluate threshold effects in MSSM for $M_e \leq 300$ GeV and $M_{\tilde{\mu}}, M_{\tilde{\tau}} \simeq (1.2-1.6)M_{\tilde{e}}$ yielding $\Delta m^2_{21} \simeq -2.7\times 10^{-5}$ eV^2 to -5.7×10^{-4}eV^2 $\Delta m^2_{32} \simeq -8 \times 10^{-6}$ eV^2 to - -3.8×10^{-4}eV^2
Such threshold effects added to the RG corrected values in [14] gives good agreement with data. Further work is in progress.

2.9 Supersymmetric Triplet Higgs Model for M^ν and high energy collider test
E.J. Chun, J. Forshaw, R. Godbole, Y.Y. Keum, S. Rindani, H. Vaidya

In scenarios with SUSY and SU(5) gauge unification neutrino masses can arise from light Triplet scalars. Such models can be tested in high energy colliders from correlated search for bilepton and leptoquarks. It was propsed to study the feasibility of such signals through numerical calculations.

2.10 Leptogenesis

Some talks and disucssions led by E.J. Chun were held on the topic of leptogeneis. Leptogenesis in models with two right handed neutrinos and in the context of type I $\oplus$ type-II seesaw scenarios was discussed. Standard leptogenesis vis-a-vis soft leptogenesis was studied. Some ideas for non-thermal leptogeneis e.g. Inflaton decays to right handed neutrino, Domain wall expansion, possible roles of inflatino were explored.

3. Astroparticle Physics

The theme of the Astroparticle Physics discussion at WHEPP-8 was particle physics implications for cosmology. With the recent interest in branes and the exciting results from the Wilkinson Microwave Anisotropy Project (WMAP) the two plenary talks were on *Brane World Cosmology* and on *Particle Physics Implications of WMAP Measurements* by Cliff Burgess and Urjit Yajnik respectively. The Working Group discussions on particle physics and cosmology were led by Manoj Kaplinghat, Ajit Srivastava and Cliff Burgess who discussed *Current and Future Measures of Absolute Neutrino Mass from Cosmology*, *Topological Defects* and *Brane Cosmology* respectively. In addition there was a seminar on *B-L Cosmic Strings and Baryogenesis* by Narendra Sahu. Subsequent discussions led to the following topics being proposed as areas of study:

• The impact of varying properties of neutrinos such as mass, mean free path, etc. on cosmic microwave background radiation fluctuations
• The effect of cosmic strings on primordial nucleosynthesis
• Constraining primordial black hole abundances from the CMBR
• Inflation and reheating in the context of branes
• The phenomenology of SUSY ADD and intermediate scale string theories
• Exploring the Randall-Sundrum model in higher co-dimensions
• Dark energy and SUSY ADD

After further discussions the efforts of the group were focused primarily on understanding how CMBR fluctuations are affected by various particle physics inputs, such as neutrino properties, the existence of cosmic strings, etc., and on explaining dark energy in the context of SUSY ADD models.

3.1 Particle Physics and CMBR
A. Dighe, M. Kaplinghat, Y.Y. Keum, B. Layek, N. Mahajan, S. More, R. Rangarajan, N. Sahu, A.M. Srivastava

Observed fluctuations in the CMBR are a function of the initial fluctuations in the energy density in various species at the time of decoupling, and other cosmological factors such as the expansion rate of the universe, the reionisation of the universe, etc. that affect the evolution of the photons as the universe evolves from decoupling till today [15]. Changing the initial fluctuation spectrum, introducing newer fluctuations after decoupling or amending the conditions in the universe as the photons propogate after decoupling can affect the observed CMBR fluctuations today. Such studies require massive numerical investigation.

Fortunately, there exists a publicly available code in Fortran/C called CMBFAST developed by U. Seljak and M. Zaldarriaga that evolves fluctuations in photons from decoupling till today while incorporating various inputs into the evolution. Effects associated with quintessence, a 5 dimensional world, interacting dark matter and gravitational lensing of the CMBR can also be incorporated. It was decided to first understand the logic of this code and to then modify it to study various issues. Below we first paraphrase a tutorial on CMBFAST presented by Manoj Kaplinghat. We then present the list of issues that were suggested for study and the modifications in the code that these entailed. Lastly we discuss the modifications that could actually be carried out during WHEPP-8.

CMBFAST

The main program of CMBFAST is cmbflat (in cmbflat.F) or cmbopen (in cmbopen.F) for a flat or an open/closed universe respectively. (For an extreme closed universe see the documentation.) These programs call subroutine fderivs that is responsible for evolving perturbations in the energy densities and pressure of baryons, non-baryonic cold dark matter, hot dark matter photons and neutrinos, and the metric perturbations. The various input parameters for the program are provided in a file called cmb.par. These include, for example, the energy densities today of the various species listed above, the vacuum energy density today, the Hubble parameter today, the nature of initial perturbation in these energy densities, the number of relativistic and non-relativistic neutrinos, reionisation parameters, etc. (See /EXAMPLES/IARGC/README and /DOC/README_IAGRC, and /EXAMPLES/IARGC/cmb.par for a sample input parameters file.) [1] The entire code is run by driver.F. The code is compatible with parallel programming. The equations underlying the code may be obtained from Ma and Bertschinger, Ap. J. 455 (1995) 7 (astro-ph/9506072). The notation used in the code is similar to that in the above paper.

The CMBFAST package may be downloaded from http://www.cmbfast.org . To start using this package, after unzipping and untarring it, type ./configure $--$with-cobe=yes $--$with-iargc=yes, which generates a Makefile, and then type make to compile and create an executable file, cmb. [2] (Additional information on configuration options is available by typing ./configure $--$help .)

The code requires tables of spherical Bessel functions. These are generated by typing ./jlgen, ./ujlgen and ./jlens . The input parameters maximum l and $keta$ were taken to be 1500 and 3000 by us and the output was stored in jl.dat, ujl.dat and jlens.dat respectively (the output filenames are an input in cmb.par). $keta$ is $k\eta_0$ where k is the wave number

[1] The README files contain fewer parameters than the sample cmb.par, and the latter contains fewer parameters than the total set of input parameters. The explanation for the parameters is in the documentation. Parameters that are not specified in cmb.par take the default values specified in subroutine setpar in params.f.

[2] On some platforms additional lines have to be added to the Makefile generated by configure to explicitly include commands to compile cmbflat.F, cmbopen.F, driver.F, subroutines.F, jlgen.F, ujlfen.F and jlens.F to prevent errors while executing the Makefile. Also on some platforms the program recfast.f has to be amended to avoid syntax errors associated with the line continuation character placed away from column 6. The RAM address extension option may also have to be invoked by replacing f77 in the Makefile by f77 -q64 on IBMSP or by f77 -oExt on Sun Workstations, etc. to avoid errors due to insufficient memory while running CMBFAST.

for the Fourier mode being evolved and η_0 is the present conformal time. (Conformal time is related to the usual co-ordinate time t by $d\eta = dt/a$ where a is the scale factor.) Maximum l and $keta$ should be larger than the corresponding values, $akmax0$ and lmo, entered in cmb.par. Note that $akmax0$ should be larger than about $2lmo$ to ensure accurate integration over k.

Now copy the cmb.par file from /EXAMPLES/IARGC/cmb.par to the directory with the executable file cmb and amend the file as required. Run the code by typing ./cmb cmb.par .[3] The output C_l coefficients for the temperature fluctuations are stored in cl_unlensed.d and cl_lensed.d (filenames are set through variables in cmb.par), which can then be plotted. The documentation contains information about other output.

We now list below the particle physics issues that the group discussed and instructions on how to change the code to calculate their impact on the CMBR. The suggested modifications to the code may not be complete.

•Neutrino masses

Neutrinos affect the evolution of the background photons in the universe in several ways. Firstly, they contribute to the energy density of the universe and hence the expansion rate. Secondly, free streaming neutrinos suppress anisotropies in matter and in photons for scales less than the mean free path of the neutrinos. Thirdly, the latter effect also affects the lensing of the CMBR by matter in the universe. Fourthly, fluctuations in the energy density in neutrinos at decoupling can affect the fluctuations in the energy density in photons. (See, for example, Refs. [16,17] for discussions of the effects of neutrinos on CMBR fluctuations.)

The energy density in neutrinos is a function of the mass. Neutrinos with masses $10^{-4}\text{eV} \leq m_\nu \leq 1\text{MeV}$ decouple when they are relativistic but are non-relativistic today and their energy density today is given by [18]

$$\Omega_{\nu nr} h_0^2 = \frac{m_\nu}{93.5\text{eV}} \frac{10.75}{g_*} \times N_{\nu nr} \tag{10}$$

where $N_{\nu nr}$ is the number of species of non-relativistic neutrinos and g_* is the number of relativistic degrees of freedom when massive neutrinos decouple. Thus to study the effect of the neutrino mass on the CMBR, the parameters to be entered into the code are $\Omega_{\nu nr}$, $N_{\nu nr}$ and g_*. These correspond to the variables $omegan$, $annunr$ and $gsnunr$ in cmb.par. [4] The neutrino mass, normalised to the temperature of relativistic neutrinos today, is calculated from the input $\Omega_{\nu nr}$ and $N_{\nu nr}$ in cmbflat.F or cmbopen.F (search for $amnu$). Currently the CMBFAST code only allows all species of non-relativistic neutrinos to have the same mass. Future work could include modifying the code to allow for neutrinos of

[3] If you get a Segmentation fault try changing nstep0=7000 to nstep0=2400 in cmbfast.inc and do make again. This is probably related to insufficient RAM. See the previous footnote for RAM address extension.

[4] $gsnunr$ does not appear in the sample cmb.par files. You may include it in cmb.par, otherwise CMBFAST uses the default value of 10.75 set in params.f.

differentmasses.

• **Time varying neutrino masses**

Time varying neutrino masses affects the energy density in neutrinos, perturbations in the energy density, the pressure and perturbations in the pressure. To incorporate this requires modifying the form of the variable $amnu$ in subroutine initinu1 in subroutines.F . Certain changes may also be required in subroutines nu1, nu2, ninu1 and nuder in subroutines.F.

• **Mean free path of neutrinos**

As mentioned earlier, this affects the spectrum of density perturbations in photons and matter. Varying the mean free path of neutrinos can be achieved by modifying the right hand side of the evolution equations for perturbations in neutrinos in fderivs. (Search for the string 'equations of motion' in fderivs.)

• **Decaying neutrinos**

This affects the evolution of the total energy density, $grho$, and pressure, $gpres$, in fderivs by changing the contribution of the neutrinos and the decay products. For the neutrinos, this can instead be incorporated by modifying $rhonu$ and pnu in subroutine ninu1 in subroutines.F. Changes may also be needed in nuder in subroutines.F. Decaying neutrinos affects the evolution equation for perturbations in the neutrinos and their decay products, which requires modifying the right hand side of the corresponding equations in fderivs and by modifying subroutine nu2 in subroutines.F. (Search for the string 'equations of motion' in fderivs.) Decaying neutrinos has been considered earlier in, for example, Ref. [19].

• **Cosmic strings**

Cosmic strings seed fluctuations in the photons continuously as they move through the background. This seed fluctuation may be modelled and inserted in subroutines fderivs and finitial where the string 'Add a seed if desired' appears.

• **Large extra dimensions**

The existence of more than 3 large spatial dimensions affects the expansion rate of the universe. This requires changes in the variables $adot$ and $adotdot$ in the subroutines fderivs, fderivst and finitthermo. These have already been incorporated in the code and the necessary changes in the code have been marked with 'DIM' in the subroutines. CMBR observations in the context of large extra dimensions have been studied in, for example, Ref. [20].

• **Interacting dark matter**

This can affect the evolution of the energy density and pressure of the dark matter and necessary changes must be made self-consistently throughout the code (e.g. in $grho$ and $gpres$ in fderivs). This also affects the evolution of the perturbations in dark matter and

can be incorporated by amending the right hand side for the evolution equations for dark matter perturbations in fderivs. (Search for the string ‘equations of motion’ in fderivs.) The effect of interactions between dark matter and baryons on the CMBR has been studied in Ref. [21].

• Decaying light gravitinos

The effect of this would depend on when the light gravitinos decay and to what they decay. To incorporate decaying gravitinos they would first have to be included in $grho$ and $gpres$ in fderivs and necessary changes would have to be made to the contribution of the daughter particles in $grho$ and $gpres$. To include perturbations, equations for the evolution of perturbations in the energy density and pressure of gravitinos would have to be included in fderivs and changes would also have to be made on the right hand side of the evolution equations for the daughter particles.

• Time varying fundamental parameters

Any time variation in the fine-structure constant alters the ionization history of the universe and therefore changes the pattern of cosmic microwave background fluctuations. The CMBR fluctuations can also be affected by a time varying gravitational constant. A time varying electron mass has a similar effect as a time varying α in that it also affects the ionisation history of theuniverse. Time varying α, G_N and electron mass have been considered in the past in, for example, Refs. [22–24] respectively. There was no further discussion of these issues at WHEPP-8. Regarding a time varying gravitational constant, note that energy densities in CMBFAST are entered as $grho$ which is the energy density times $(8\pi/3)G_N a^2$, where G_N is Newton’s gravitational constant (see fderivs). The pressure, $gpres$, and perturbations in the energy density and pressure, $dgrho$ and $dgpres$, are defined similarly.

Much of the effort at WHEPP-8 was devoted to identifying where modifications would be needed in the code to incorporate various interesting particle physics ideas. These have been listed above. In the remaining time available, time varying neutrino masses were studied with a trial parametrisation of the neutrino mass as below:

$$m(t) = \bar{m}\exp[-\,(a/a_{nr})^{\frac{1}{n}}]\,, \tag{11}$$

where a_{nr} is the scale factor when the neutrino becomes non-relativistic. The variation of the CMBR fluctuations for constant mass and $n = 10$ are given in Fig. 1. However not all changes may have been made consistently in CMBFAST.

The code was also modified to incorporate one massive neutrino species decaying to massless neutrinos. At WHEPP-8 we were able to modify the code to alter the evolution equations for the decaying particle but not the daughter particles. One hopes that this will be addressed in the future. If the code is modified to include massive neutrinos of different masses, one could also consider scenarios where one massive neutrino decays to a lighter massive neutrino.

Some effort was made to incorporate cosmic string seeded perturbations in the CMBR but some issues regarding the nature of the perturbation needed to be resolved.

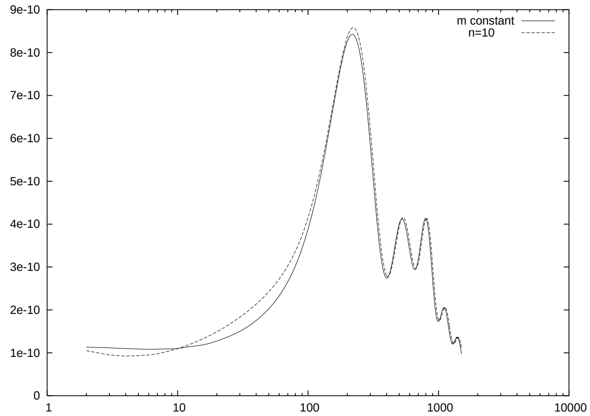

Figure 1. C_l vs l for constant mass and $n = 10$

3.2 Brane Cosmology
C. Burgess, N. Gupta, Y.Y. Keum, P. Ramadevi, U. Yajnik

At WHEPP-8 there were some prelimnary discussions on reheating in the context of branes. The remaining discussions were on Supersymmetric ADD and Dark Energy, as given below.

• Supersymmetric ADD and Dark Energy

There have been proposals to explain the origin of the Dark Energy in a natural way using extra dimensions and supersymmetry. The scheme pursued in [25] was reviewed. Its proposal consists of having the observed Universe as a brane in 6 dimensional space-time. There are also other similar branes and the theory to begin with is supersymmetric. The interest in 6 dimensions is justified from the ADD [26] observation that the current experimental limits permit a brane world compactification scale r_c as large as 2 mm, which corresponds to

$$\frac{1}{r_c} \sim M_c \sim \frac{M_{EW}^2}{M_{Pl}} \sim 10^{-4} eV \tag{12}$$

Supersymmetry ensures a natural value for the vacuum energy to be zero. The *small* vacuum energy can then be obtained as follows.

The $N = 1$ supersymmetry of 6 dimensions manifests as $N = 2$ supersymmetry in 4 dimensions. The presence of the brane breaks translation invariance and hence supersymmetry. However it has been shown [27] that the breaking of translation invariance leads to the breaking of precisely one of the two supersymmtries on the brane. Which supersymmetry breaks is decided by the winding number of the brane treated as a vortex solution in 6 dimensions. If there are several branes present it can be arranged that another brane has the complementary supersymmetry broken due to opposite winding number. As a result, the complete supersymmetry of the 6 dimensions is broken. However each of the branes possesses an approximate supersymmetry, broken to a small extent by the breaking caused on

the other brane. On phenomenological grounds we expect the supersymmetry on our brane to be broken at the electroweak scale M_{EW}. It has been argued that in this case the splitting of the gravity supermultiplet in the bulk would be of the order $\Delta M_{SUSY} \sim (M_{EW}^2)/M_{Pl}$.

One can now compute the conserved vacuum energy in the following scheme.

$$\begin{aligned}\lambda_{eff} &= \text{brane tensions} + \text{bulk curvature} + \text{bulk loop corrections} \\ &= \sum_i T_i + \int d^2y\sqrt{-g}(R + F^2 + ...)\end{aligned} \tag{13}$$

However the source of the bulk gravity are the branes, so that the first two terms cancel. Then the bulk loops provide

$$\lambda_{eff} \approx (\Delta M_{SUSY-bulk})^4 \sim \left(\frac{M_{EW}^2}{M_{Pl}}\right)^4 \tag{14}$$

being precisely $(10^{-4}eV)^4$ matching the observed vacuum energy and also within the experimental limits of gravity experiments.

One important issue faced by the scenario is stabilising the distance scale between the branes so that the variation of the vacuum energy is slow enough to not contradict the approximately constant value of current cosmology.

There are further contributions to the λ_{eff} from subleading terms. The problem is a systematic assessment of these contributions. In [25] these contributions were computed in Salam-Sezgin [28] 6D Supergravity model. It was shown that we can order these contributions in powers of a cutoff Λ.

$$\delta V_{eff} \sim \Lambda^6 + \Lambda^4 + \frac{\Lambda^2}{r_c^2} \tag{15}$$

where the first two terms can be shown to be well controlled but the third needs further verification. It would be interesting to pursue a calculation within the Supergravity model compactified on a two-sphere, $\mathbb{R}^4 \otimes S^2$, with two branes of opposite winding numbers present.

ACKNOWLEDGMENTS

S.G. would like to acknowledge help from K. Agashe, A. Dighe, Y. Nir and P. Mehta in preapring the section on Neutrino Physics. R.R. would like to thank Manoj Kaplinghat, Surhud More and Urjit Yajnik for help in preparing the section on Astroparticle Physics.

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